The FNAL Proton Complex and its Evolution for NuMI and mu2e

Dave McGinnis

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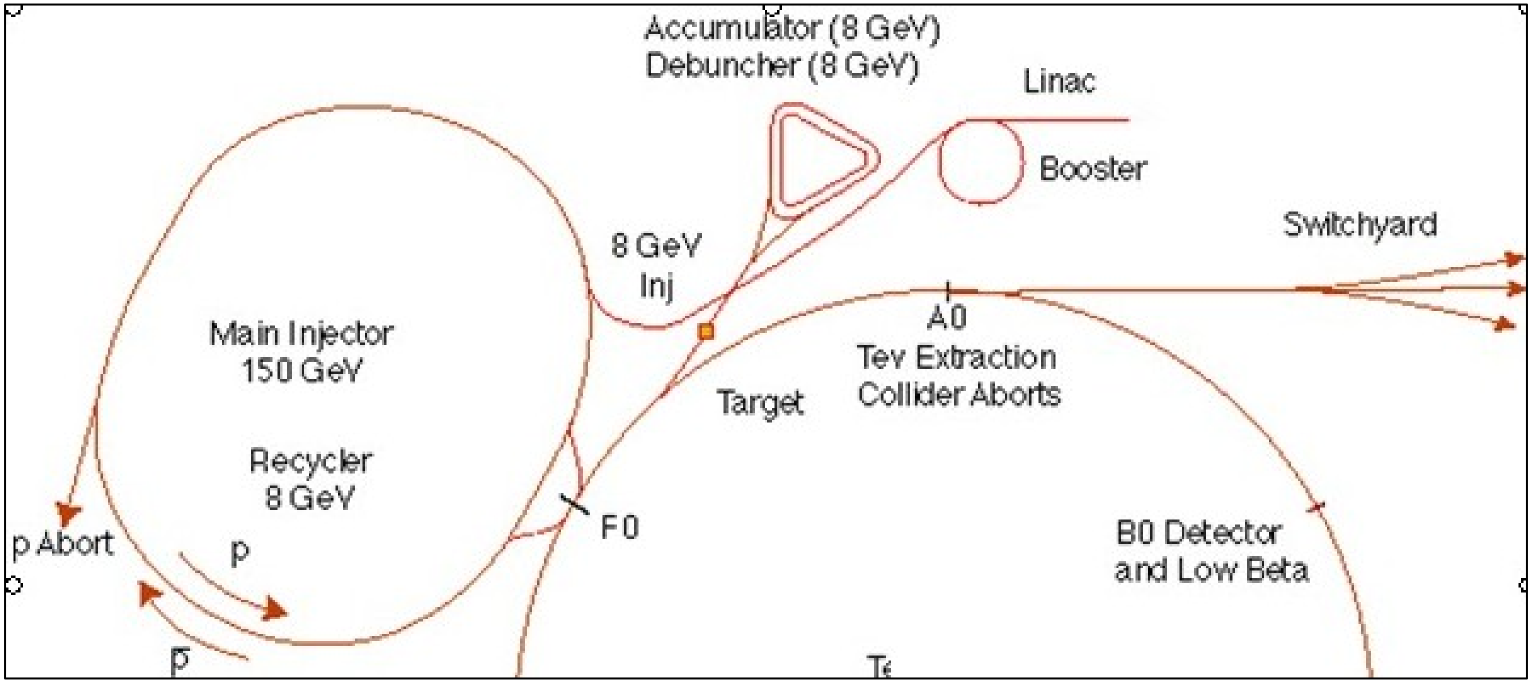
Present Fermilab Proton Source

- The FNAL Linac accelerates H- to 400 MeV
- The FNAL Booster accelerates protons to 8 GeV.
- The 8 GeV protons are used for MiniBooNE and to feed the Main Injector.
- The Main Injector accelerates protons to 120 GeV.
- The MI protons are used to make antiprotons (Collider) and neutrinos (MINOS).
- The Tevatron Collider uses three additional proton source rings (Debuncher, Accumulator, and Recycler).



Multi-stage Proton Accumulator Introduction

- Develop an alternative plan to provide high intensity proton beams beyond 2010
- The plan needs to have the following important features
  - It must be inexpensive
  - It must be completed quickly
  - It should not shutoff the collider complex or the neutrino program for an extended period of time.
- These goals can be accomplished only if:
  - It uses the present Fermilab infrastructure (tunnel enclosures, service buildings, power, utilities, etc.)
  - The project is staged
- After the collider program concludes, the present antiproton production complex can be converted into a multi-stage accumulator for 8 GeV proton beams
  - Accumulator -> Momentum Stacker
  - Recycler
    - Stand alone slip stacking
    - Or Box Car Stacker in series with momentum stacking in the Accumulator

Project Staging

- Because the concept uses existing infrastructure the performance can be broken into stages
- Project staging has the important benefit of providing
  - a fraction of the total performance
  - at a fraction of the total cost
- The schedule for each stage is driven by physics need and funding availability
- Each stage is based on standard accelerator technology and accelerator parameters that are currently achievable.

Stages

- Stage 1: The Proton Plan.
  - Booster aperture upgrades
  - Slip stacking in the Main Injector
- Stage 2: SNUMI 1*
  - Slip Stacking in the Recycler
  - Main Injector "Load and Go"
    - Main Injector Cycle time reduces from 2.1 sec to 1.3 sec
- Stage 3: SNUMI 2*
  - Proton momentum stacking in the Accumulator
  - Box Car stacking in the Recycler
  - Main Injector "Load and Go"

*See Talk at by Alberto Marchionni

Booster Throughput Scenarios

- All the proton upgrades rely on increased Booster throughput

Parameter	Sept. 2005	Prot. Plan	SNUMI 1	SNUMI 2a	SNUMI 2b	
Booster Flux	6.4	13.5	13.1	22.6	25.1	$x10^{16}$/Hr
Collider Flux	1.1	1.5	0.0	0.0	0.0	$x10^{16}$/Hr
NUMI Flux	3.2	7.5	13.1	22.6	20.5	$x10^{16}$/Hr
NUMI Beam Power	162	372	648	1181	1073	kW
8 GeV Flux	2.1	4.5	0.0	0.0	4.6	$x10^{16}$/Hr

Parameter	Sept. 2005	Prot. Plan	SNUMI 1	SNUMI 2a	SNUMI 2b	
Collider Final Intensity	6.9	8	0	0	0	$x10^{12}$
NUMI Final Intensity	22	40	45	82	82	$x10^{12}$
MI Cycle Time	2.60	2.07	1.33	1.33	1.47	Sec
Collider Batches	2	2	0	0	0	
NUMI Batches	5	9	12	18	18	

Multi-stage Proton Accumulator Motivation

- Slip stacking multiple Booster batches in either the Main Injector or the Recycler is the central concept for proton fluxes up to 14×10^{16} protons/hour
  - Longitudinal stacking at 8 GeV reduces the peak intensity requirement in the Booster
  - Results in a smaller required aperture for the Booster
    - Smaller space charge tune shift
    - Reduced requirements on acceleration efficiency
- Above 14×10^{16} protons/hour, the number of batches stacked into the Recycler can not be increased further by slip stacking because of the rather severe amount of emittance dilution that is fundamental to the slip stacking process.
- Momentum Stacking has much smaller longitudinal emittance dilution than slip stacking and can be used in place of slip stacking to achieve proton fluxes greater than 14×10^{16}

Beams Document 1782

A 2 Megawatt Multi-Stage Proton Accumulator

1 Introduction

1.1 Motivation

The delivery of high intensity proton beams for neutrino experiments is a core element of the Fermilab physics program for the next decade and beyond. This document outlines a plan which will greatly enhance the intensity capability beyond the year 2010 should budget and approval for the Proton Driver Linac fail to materialize. In order to reduce costs and to minimize disruption to the ongoing program, the plan uses existing infrastructure (tunnel enclosures, service buildings, power, utilities, etc.). The cost scale is estimated to be less than $100M, and the plan could be fully implemented by 2012 without the need for an extended shutdown period.

The use of existing infrastructure allows the plan to be broken into stages. Project staging has the important benefit of providing a fraction of the total performance at a fraction of the total cost. The schedule for each stage is driven by physics need and funding availability.

1.2 Concept

Multi-turn injection into the Booster is the current process for obtaining high intensity proton bunches in the Main Injector for neutrino experiments. Because of the relatively small aperture of the Booster and the large space charge tune shift at Booster injection, proton loss at injection limits the number of protons per bunch. Since space charge effects rapidly decrease with energy, it is more desirable to increase the proton intensity at higher energies. Due to the rapid cycling nature of the Booster, many Booster batches can be quickly combined at the Booster extraction energy. Because the bunch length requirements for neutrino experiments are not strict, the best technique to combine multiple Booster batches is to coalesce them longitudinally.

Slip stacking multiple Booster batches is the central concept of the Proton Plan[1]. In Stage 1, while the collider program is still running, nine Booster batches will be slipped stacked in the Main Injector for the neutrino program. In Stage 2, when the Recycler becomes available after the collider program is concluded, the slip stacking will be done in the Recycler which can handle 33% more batches with a 30% decrease in the cycle time. The number of batches stacked into the Recycler can not be increased further by slip stacking because of the rather severe amount of emittance dilution that is fundamental to the slip stacking process.

Another large increase in proton intensity is possible after the collider program concludes because the present antiproton production complex can be converted into a multi-stage proton accumulator for injection into the Main Injector. This accumulator would have three major components, each re-using or replacing existing machines:

- The Accumulator ring as a RF momentum stacker.
- The Recycler ring as a box-car stacker.
- The Debuncher ring would be replaced with a wide aperture booster.

1.2.1 RF Momentum Stacking in the Accumulator

The center piece of this concept is RF momentum stacking in the Accumulator. The key features of RF momentum stacking are a large momentum aperture and injection system located at high dispersion. Because the same features are required for stochastic momentum stacking of antiprotons, RF momentum stacking in the Accumulator would be possible with only minor modifications to the Accumulator.

During momentum stacking, a Booster batch is placed on the injection orbit of the Accumulator and accelerated towards the high energy aperture as shown in Figure 1-1. Another Booster batch is injected onto the injection orbit and accelerated towards the high energy aperture and deposited adjacent to the previous batch. The limit to how many Booster batches can be stacked is not the Accumulator aperture but the momentum aperture of the Main Injector at the transition energy. With present Booster performance, the Main Injector momentum aperture can comfortably handle over four Booster batches. This large number of batches can be combined using momentum stacking because momentum stacking has very little longitudinal emittance dilution.

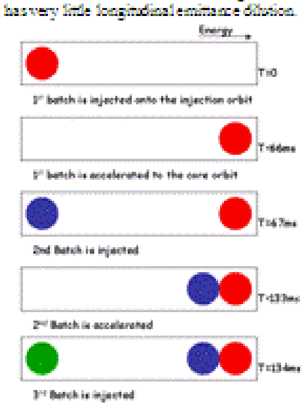


Figure 1-1 Cross-section of the transverse aperture in high dispersion of the Accumulator during momentum stacking.

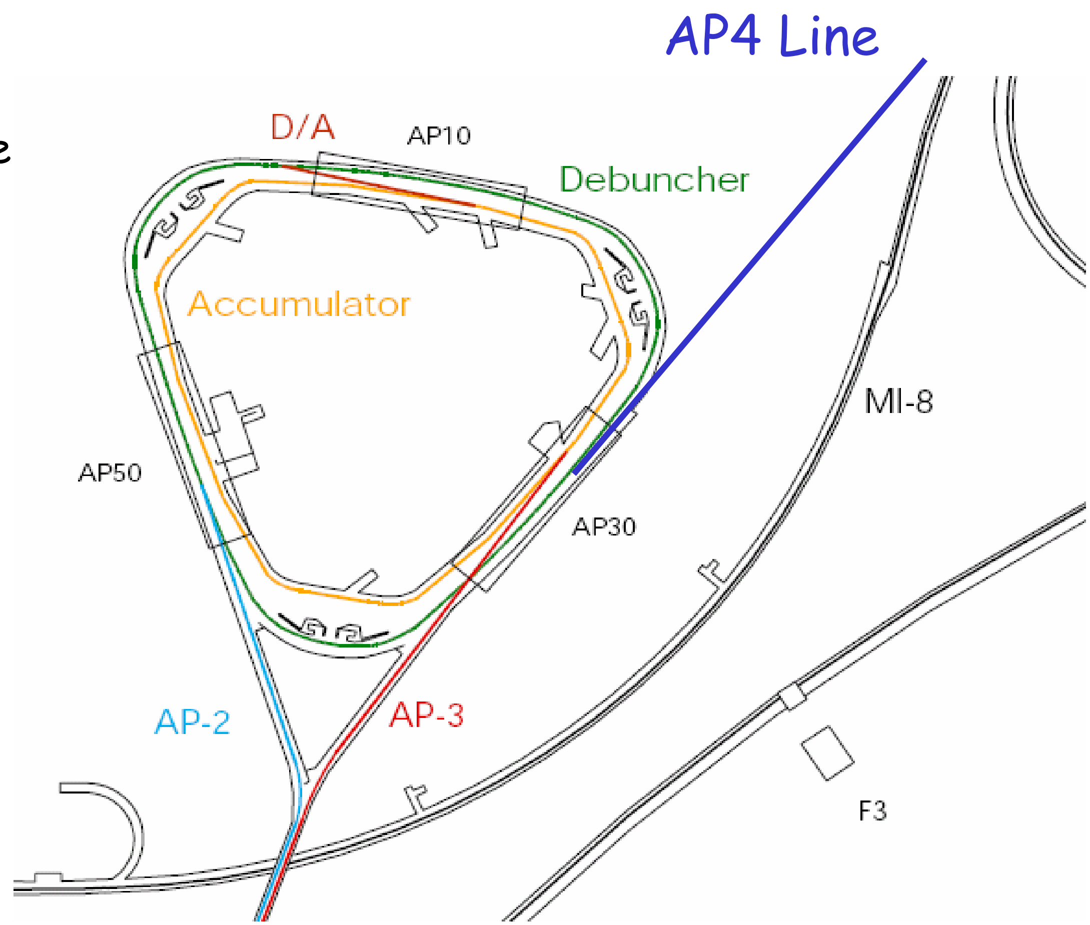
1.2.2 Box Car Stacking in the Recycler

Once at least three to four Booster batches have been momentum stacked in the Accumulator, the coalesced proton stack would be transferred to the Recycler. Since the Accumulator circumference is one seventh of the Recycler circumference, five more Accumulator stacks can be placed one after the other in the Recycler (box-car style) while leaving one seventh of the ring as an abort gap. The Recycler fully loaded in this manner would contain twenty four Booster batches which is twice the number of batches

http://beamdocs.fnal.gov/AD-public/DocDB/ShowDocument?docid=1782

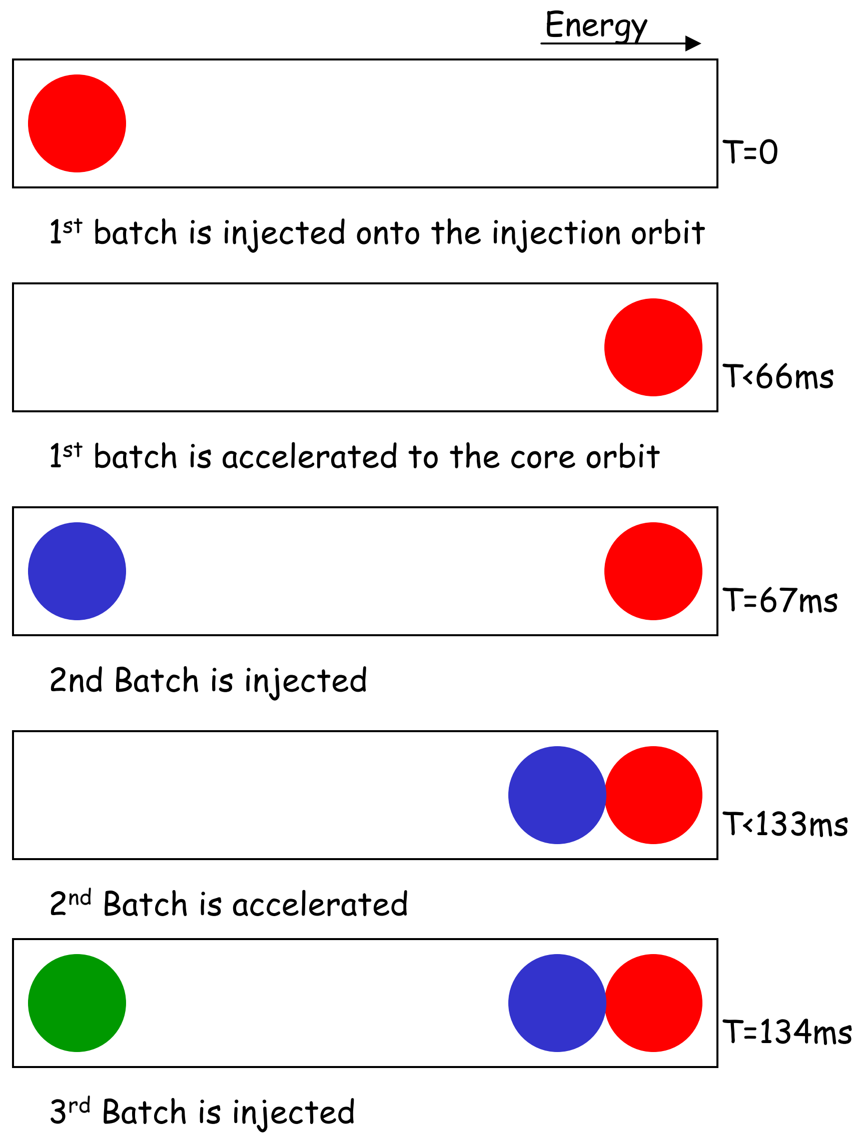
Concept - Momentum Stacking in the Accumulator

- After acceleration in the Booster, the beam will be transferred DIRECTLY to the Accumulator ring
- The Booster is connected to the Accumulator via a new AP4 Line
- The line comes in A30 underneath the Debuncher
  - It must cross underneath the Debuncher and rise to the same elevation as the accumulator
  - The Accumulator injection septum is moved from downstream A10 to the downstream A30
  - The Accumulator Injection kicker is moved from upstream A20 to upstream A40
- The new AP4 line is about 240 meters in length
  - Use magnets from the AP2 line for 8 GeV operation
  - Civil Construction 5 M$



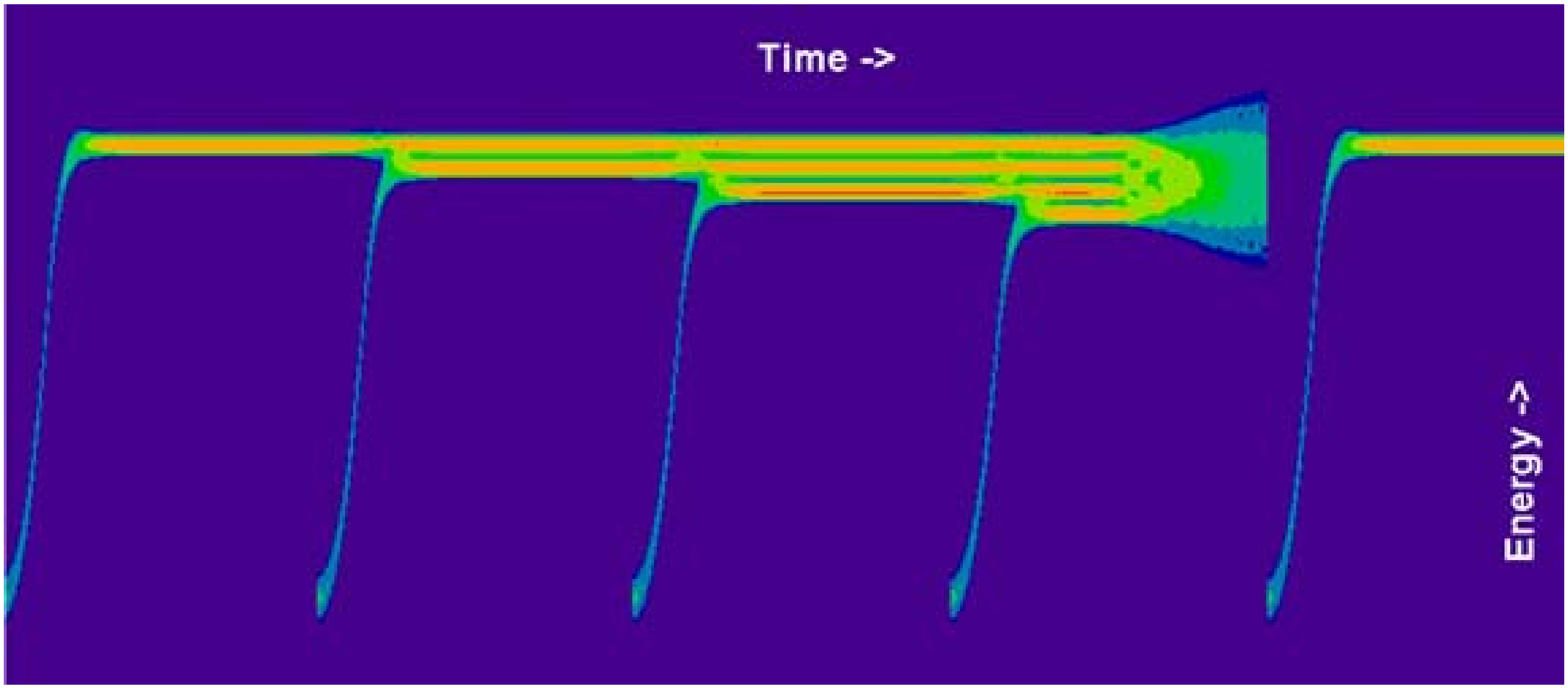
Mechanics of Momentum Stacking

- The Accumulator was designed for momentum stacking
  - Large momentum aperture ~ 84 x 2.8 eV-Sec
  - Injection kickers are located in 9m of dispersion
  - Injection kickers do not affect core beam
- Inject in a newly accelerated Booster batch every 67 mS onto the low momentum orbit of the Accumulator
- The freshly injected batch is accelerated towards the core orbit where it is merged and debunched into the core orbit
- Momentum stack 3-4 Booster batches



Momentum Stacking

Output longitudinal emittance = 84 * 0.38 eV-sec



Input longitudinal emittance = 84 * 0.08 eV-sec

Advantages of Momentum Stacking

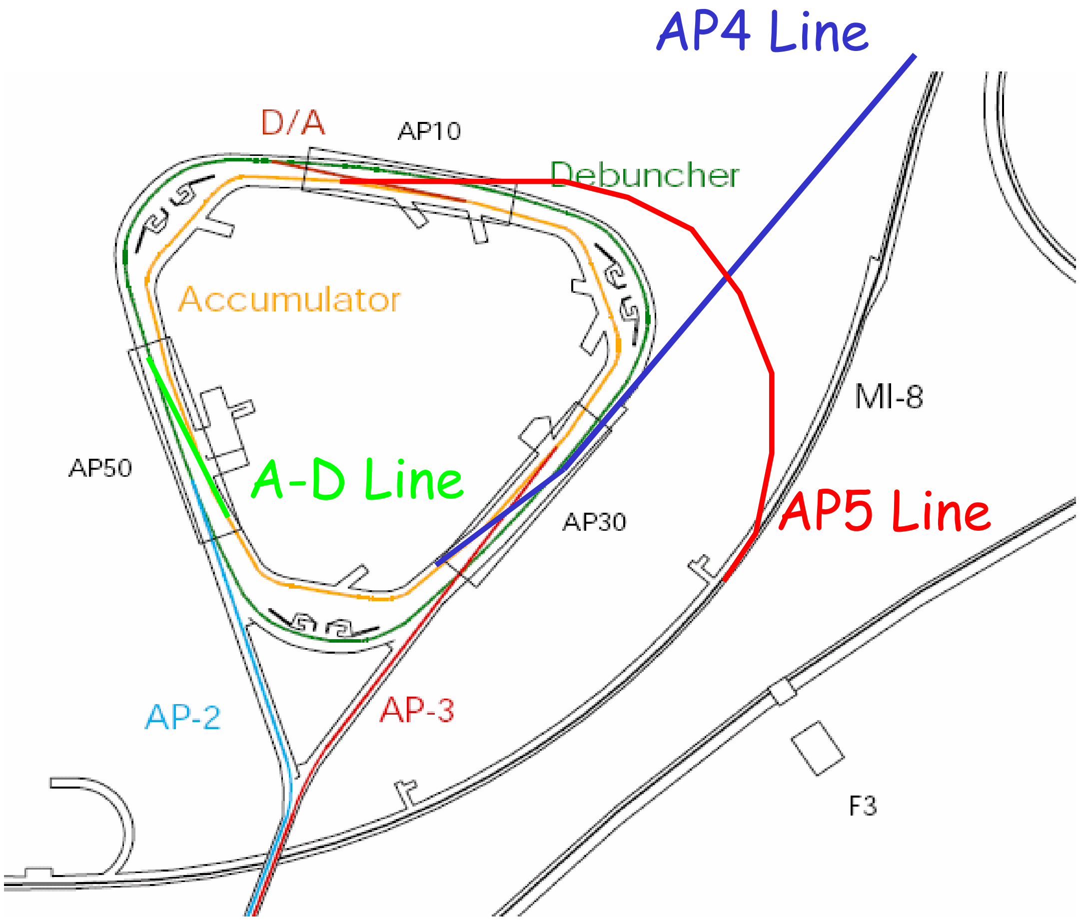
- Transient Beam Loading
  - Slip stacking or barrier bucket stacking requires manipulating intense beams with low RF voltages in a mostly empty circumference
  - In momentum stacking, the circumference is always uniformly loaded
- Speed of process
  - Injected beam can be decelerated quickly towards the core beam
- Longitudinal emittance dilution
  - The core beam can be debunched during stacking process reducing the amount of "white spaces"
- Cogging in the Booster
  - Prior to injection into the Accumulator, the injection orbit of the Accumulator is empty
  - The Accumulator injection system can be phase-aligned to the Booster which eliminates cogging in the Booster
  - The Booster notch can be made in the Linac

Multi-stage Proton Accumulator Scheme

- Momentum stack in the Accumulator
  - Inject in a newly accelerated Booster batch every 67 mS onto the high momentum orbit of the Accumulator
  - Decelerate new batch towards core orbit and merge with existing beam
  - Momentum stack 3-4 Booster batches
  - Extract a single Accumulator batch
    - Every 200 – 270 mS
    - At an intensity of 3-4x a single Booster batch
- Box Car Stack in the Recycler
  - Load in a new Accumulator batch every 200-270mS
  - Place six Accumulator batches sequentially around the Recycler
- Load the Main Injector in a single turn

AP-5 Line

- The Accumulator is connected to MI-8 line for SNUMI injection via the new AP5 Line
- The Accumulator extraction kicker is moved from downstream A20 to downstream A60
- The Accumulator extraction lambertson is moved from upstream A30 to upstream A10
- The AP5 line bends towards the MI-8 line with the same radius as the Booster
- The AP5 line must drop ~20' during the bend to reach the MI-8 elevation



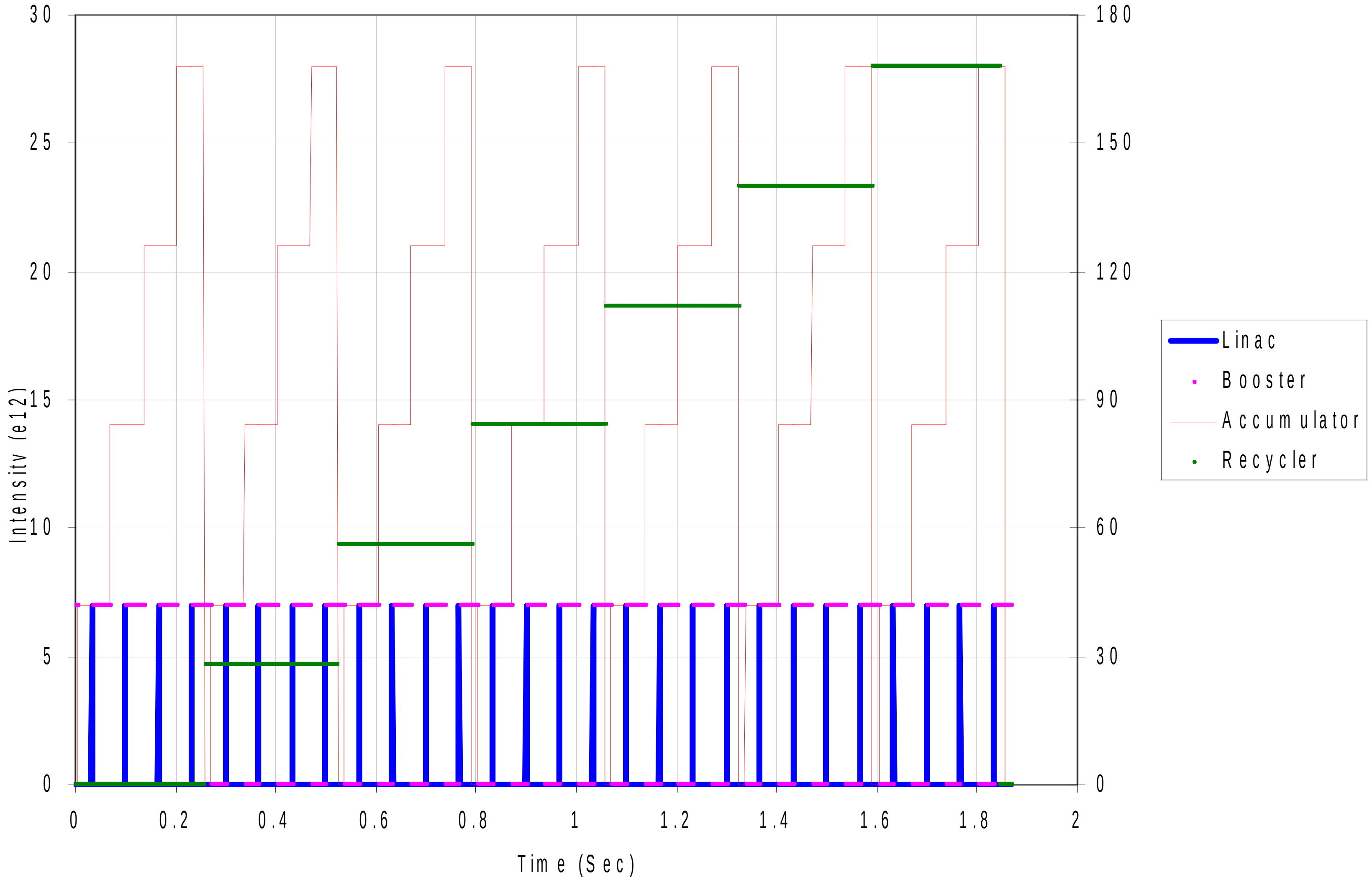
Extraction From the Accumulator

- After 3-4 batches have been stacked begin preparing to extract all the beam from the Accumulator to the Recycler
- Re-bunch the entire stacked beam at h=12 in the Accumulator (7.5 MHz)
  - Low harmonic for a large enough gap between buckets which could accommodate kicker rise time
  - High harmonic for fast synchrotron period for the speed of the process
  - New system –need 30 kV/Turn in Accumulator

Box Car Stacking in the Recycler

- After 3-4 booster batches have been momentum stacked in the Accumulator, the beam would be transferred to the Recycler.
  - 7.5 MHz MHz synchronous transfer
    - New system
    - Need 80kV/Turn for a 4.2 eV-sec bucket
  - Accumulator phase ALIGNED to the Recycler
- The Accumulator is 1/7 of the Recycler's circumference
- Boxcar stack six of the Accumulator batches leaving 1/7 of the Recycler ring for an abort gap.
- After 6 Accumulator batches have been stacked into the Recycler debunch 7.5 MHz beam in >80mS
- Re-capture in 53 MHz buckets for acceleration.
  - Need 500 kV for 0.6 eV-sec
  - 53 MHz RF system will be installed for slip stacking in the Recycler for the 700kW stage.

Multi-stage Proton Accumulator Production Cycle



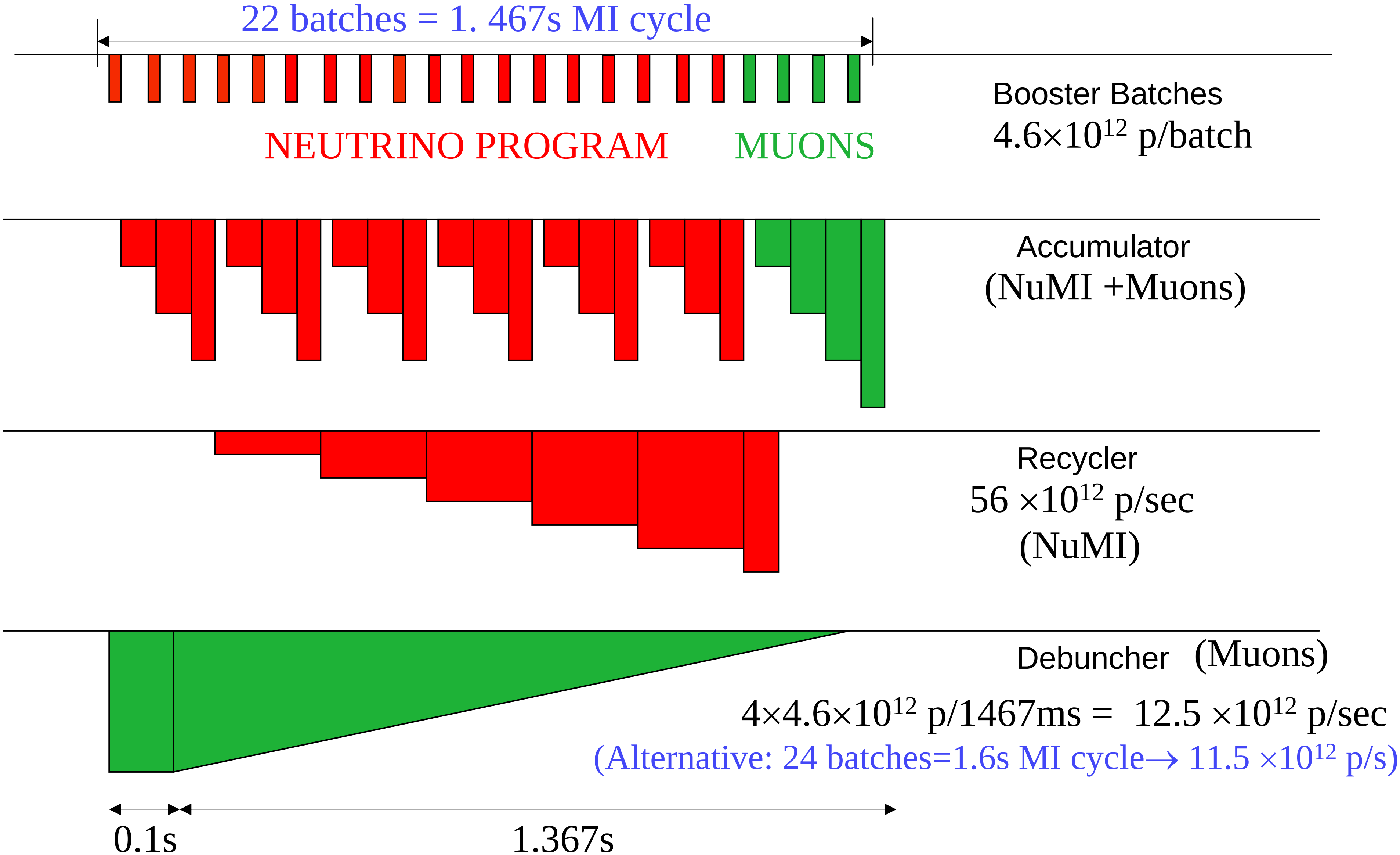
Multi-stage Proton Accumulator Issues

- Once the SNUMI group provides a conceptual design report for slip-stacking in the Recycler, it will begin to further develop the concept of momentum stacking in the Accumulator.
- List of Issues
  - Booster throughput
  - Transfer line design
  - Space charge effects in the Accumulator and Recycler
  - Radiation shielding
  - Beam-loading
  - Transition crossing in the Main Injector
  - Instabilities (electron cloud, coupled bunch, etc.)
  - Etc…

Multi-stage Proton Accumulator at 1.1MW Cost Estimate in k$

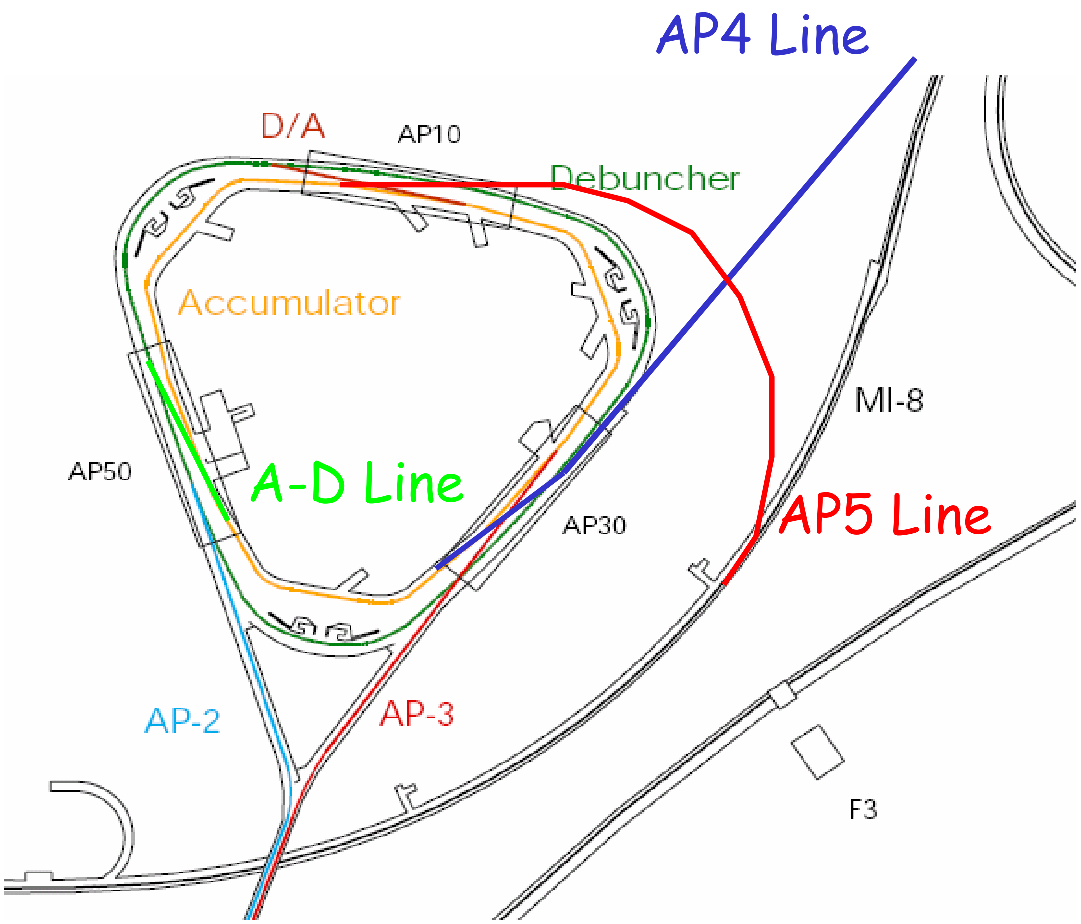
Description	Cost
AP4 Line Civil	4,500
AP4 Tie In & Installation	1,000
AP3 Modification Civil	3,000
AP3 Tie In & Installation	1,000
Accumulator Shielding	3,000
Accumulator Kickers	1,000
Accumulator 53 MHz RF	600
Accumulator 7.5 MHz RF	600
Accumulator Instrumentation	300
Main Injector RF	12,500
NUMI	3,500
Total	31,000

Mu2e and SNUMI



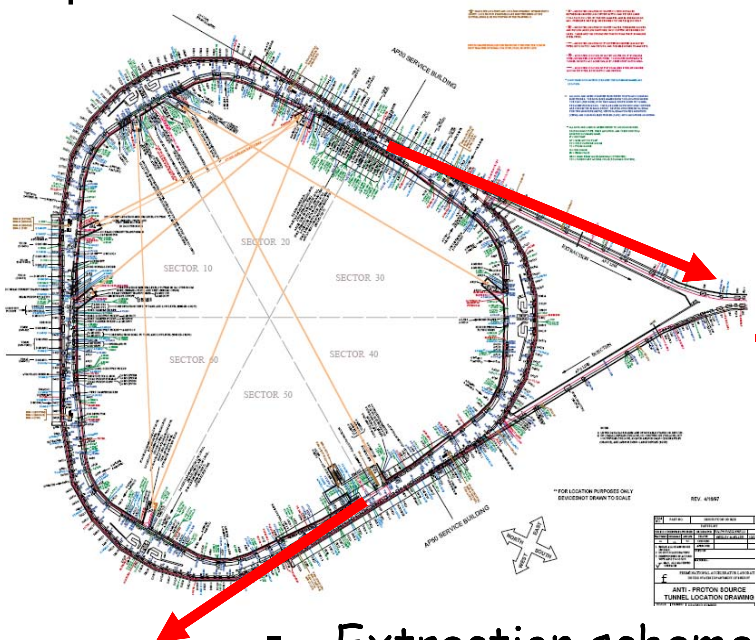
Slow Extraction in The Debuncher

- The Accumulator is connected to the Debuncher for μ-to-e injection via the reversed D-A line (A-D line)
- The Accumulator injection kicker is moved from upstream A20 to downstream A40
- A new Accumulator septum is placed at upstream A50
- The A-D line connects to the Debuncher at downstream D50
- The Debuncher extraction septum at upstream D10 is moved to be an injection septum at downstream D50



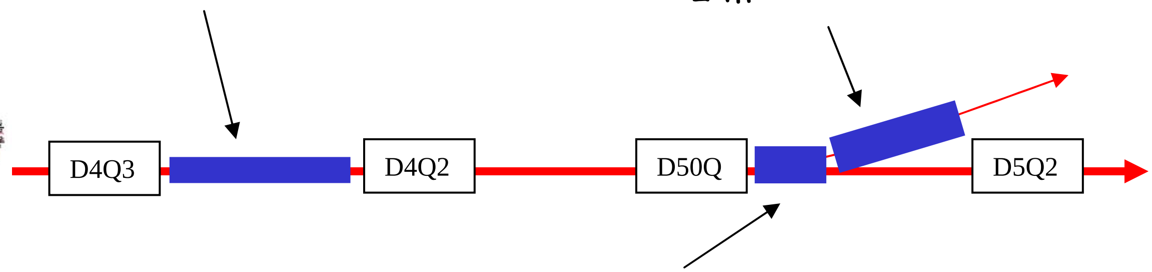
Resonant Slow Extraction*

options:



MI/TeV style septum
- 80kV/1cm field region
- 3 m long

Wide aperture C magnet
- ~.8 T
- 2 m



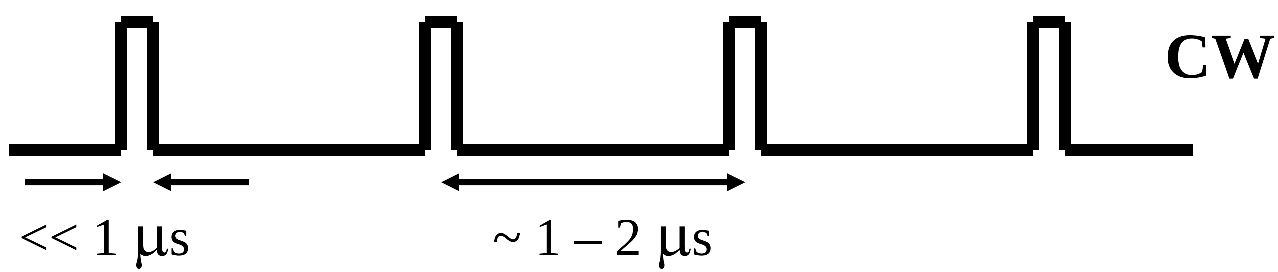
Short version of MI style Lambertson
- ~ .8T field region
- +- 5" extraction aperture
- 1 m long

- Extraction scheme appears workable
- Studying details of resonance generation
  - Also comparing 2nd integer vs. 3rd integer
- Extraction loss a worry
  - ~ 500W loss with typical (2-3%) resonant extraction inefficiencies
  - Must be considered from the beginning in the design

*See Talk at by Eric Prebys

Beam Requirements

- To reach MECO goal: Requires ~10^{20} primary 8 GeV protons per year with the right bunch structure.
- Bunch lengths short compared to the lifetime of muons orbiting a nucleus (1.1 ms for Al)
  - with a bunch spacing longer than this time
  - but not too much longer since we want to minimize peak rates.
- Experimental signature:
  - mono-energetic electron & nothing else.
  - To minimize backgrounds, when there is no incoming primary beam there must be no beam at the level of 1 part in 10^9.
- Ideal Bunch Structure for the slow muons (& for the primary protons)



Proton Beam Specification

Example: 4.6×10^{12} protons per Booster Batch & a 1.467s MI cycle

Beam Energy	8 GeV
Bunch Trains / sec: f_{TRAIN}	0.682
Bunch Spacing: ΔT_B	1.6 μs
No. of bunches/train: N_B	85×10^4
No. protons/bunch: n_P	2.16×10^7
Bunch Length (2.5s) : t_B	150 ns (s=60ns)
Protons/train (4 batches)	1.84×10^{13}
Protons/year (10^7 secs)	1.25×10^{20}

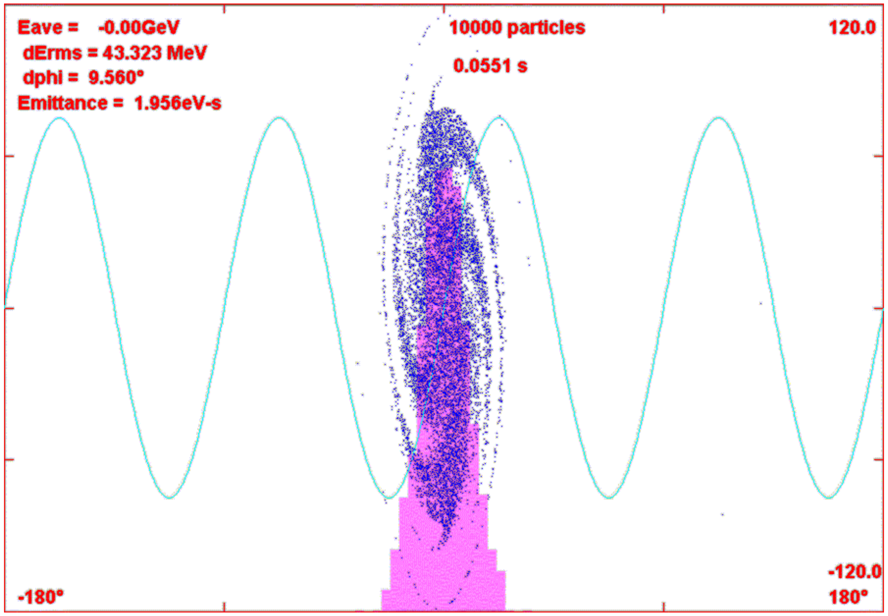
Four years running $\rightarrow 5 \times 10^{20}$ protons $\rightarrow 1.3 \times 10^{18}$ stopped muons

Beam Bunching for mu2e*

- Bunch beam to a fraction of the Debuncher circumference
  - < ~200ns of 1700ns
- Keep beam leakage outside that bunch length to a minimum
- Debuncher timings are similarto MECO/BNL
- Develop most effective/efficient bunching scheme
  - barrier bucket
  - Multi-harmonic
- Will need a fast kicker in the Debuncher ring to further clean gap.

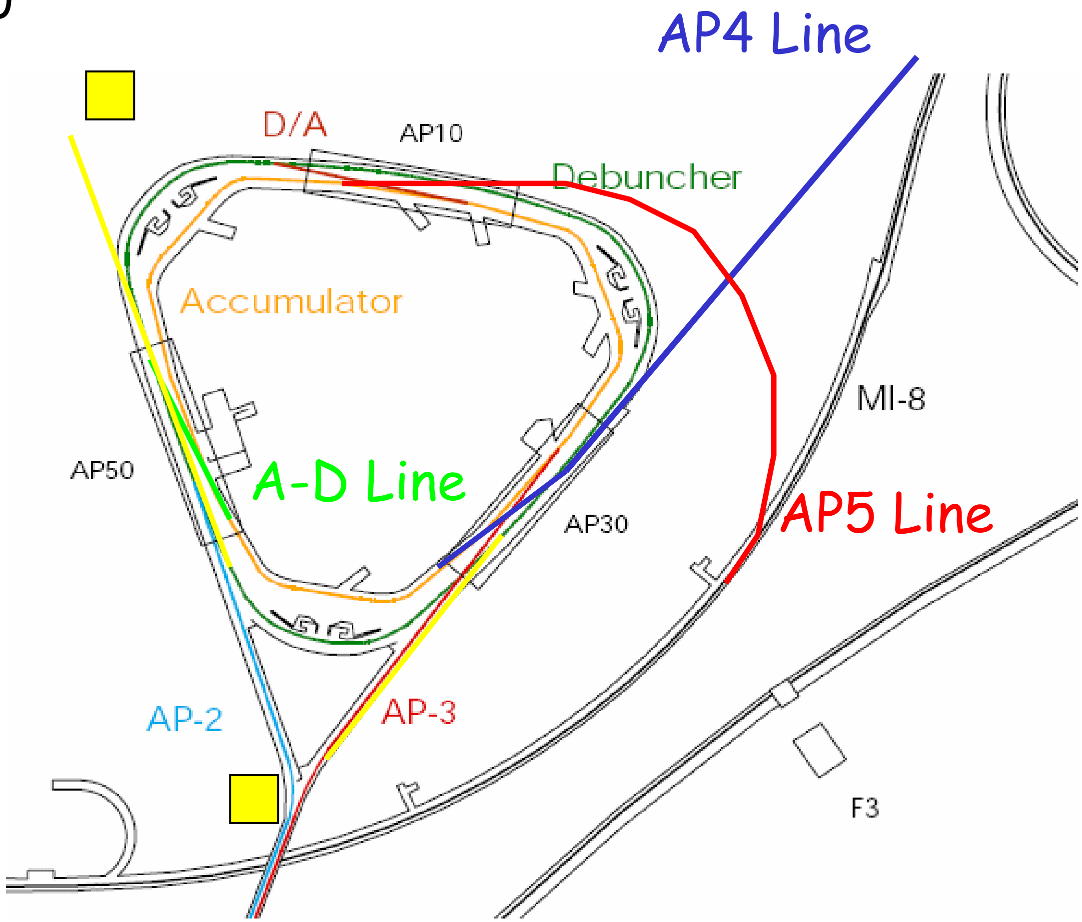
*See Talk at by Dave Neuffer

- Multi-harmonic example
  - rf multi-harmonic buncher
    - Example: h=1, V_{rf}=30kV; h=2, Vrf = 15kV, h=3, V_{rf} =10kV
    - h=4: 7.5 →50kV (to hold compressed beam)
  - 0.055s for bunching



μ-to-e Extraction Line

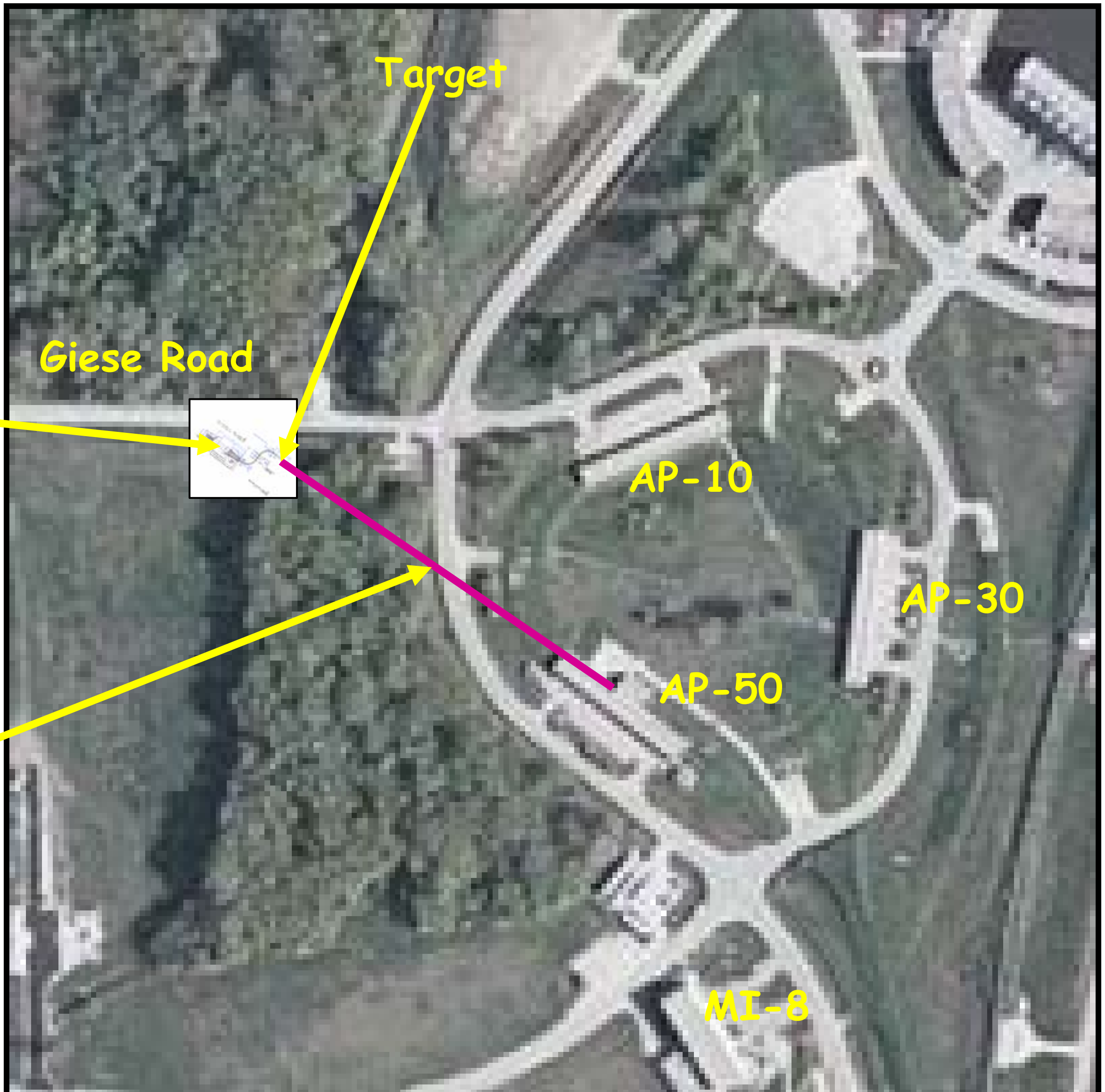
- The beam is slow spilled extracted from the Debuncher at either D30 or D50
- At D30, the extracted beam goes towards AP3
- At D350, the extracted beam heads west



Location of Mu2E target and Detector*

Detector

Extracted Beam Line From Debuncher



*See Talk at by Dixon Bogert

Mu2e Additional Accelerator Issues

- Slow Spill system in the Debuncher
- Beam loss in the Debuncher
- Extinction of unwanted particles in bunch gap
- Fast Kicker design for beam cleaning
- Dump design for beam cleaning
- Transfer line design to experiment

Summary

- Momentum stacking has much smaller longitudinal emittance dilution than slip stacking and can be used in place of slip stacking to achieve proton fluxes much greater than 14×10^{16}/hour
- Because the Accumulator was designed for momentum stacking, the present antiproton production complex can be converted into a multi-stage proton accumulator
  - Accumulator -> Momentum Stacker
  - Recycler -> Box Car Stacker
  - Debuncher -> Slow Spill to mu2e
- The multi-stage proton accumulator can supply enough protons for a 1.1 MW 120 GeV beam and 1×10^{20} 8 GeV protons / year for mu2e.